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FREE SURFACE VELOCITY PROFILES IN MOLYBDENUM SHOCK COMPRESSED AT 1400°C

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The equation of state, constitutive properties and unloading wave velocities of molybdenum have been determined from free surface velocity profiles on samples shock compressed from a 1400°C initial state. The equation of state of 1400°C molybdenum agrees with previous streak camera measurements and the combined equation of state between 12 and 96 GPa is: $U_S = 4.78\ (0.02) + 1.42\ (0.02)\ u_p$. Unloading wave velocities measured between 12 and 81 GPa range from 6.30 to 7.91 km/s and are 4-8% below extrapolated 25°C compressional velocities. The yield strength, Y, was found to be 0.79-0.94 GPa, compared with values of 1.3-1.6 GPa from ambient-temperature experiments.

INTRODUCTION

Shock-compression methods are uniquely capable of producing high pressure (P) and high temperature (T) states of matter. One limitation of shock techniques is that pressure and temperature cannot be varied independently (for non-porous samples). By shock compressing a sample preheated to a known high temperature, it is possible to delineate the separate effects of P and T on material properties.

In this study, we report new wave profile measurements on molybdenum shock-compressed between 12 and 81 GPa from a 1400°C initial state. The results provide insight into the effects of temperature on the elastic, constitutive, and equation of state (EOS) properties under shock compression. For the first time, we have extended the range of optical velocity interferometric techniques to materials at significantly high initial temperatures (>250°C).

EXPERIMENTAL TECHNIQUE

Molybdenum (Mo) was chosen for study because of its role as a high-pressure standard. In addition, its 1400°C equation of state (EOS) has been studied previously [1], and shock compression data above 150 GPa [2] reveal complex behavior. Shock compression of Mo (99.95% purity) was carried out using foam-backed aluminum and tantalum flyer plates to impact 5.5-mm thick Mo samples with velocities between 0.95 and 2.28 km/s. Prior to impact, the samples were heated to near 1400°C using a radio-frequency heating system [1], and the temperature was measured to ±1°C by a thermocouple. The motion of the rear free surface of the Mo sample was recorded using a VISAR. The time resolution of our VISAR is ~2–3 ns, the precision is ±1%, and velocity changes of a few m/s are resolvable.

RESULTS

Four experiments were conducted on Mo samples, three of which yielded free surface velocity profiles. In the fourth experiment, data recording failures prevented a wave profile from being obtained but the arrival times of the shock front and the initial unloading wave could be read from the partial fringe records. The velocity profiles are shown in Fig. 1.

Compressive States

To establish timing for the experiments, the toe of the elastic precursor was assumed to propagate at the ambient-pressure compressional wave velocity which was calculated to be 6.10 km/s from the linear modulus-temperature trend in high T ultrasonic data to 700°C [3]. The time difference between the precursor and the midpoint of the shock established the shock velocity and, together with the particle

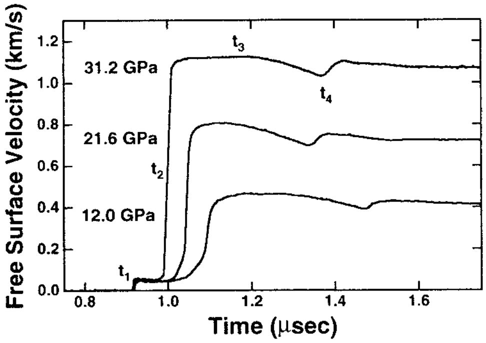

Fig. 1. Free surface velocity histories recorded at the rear surface of 1400°C molybdenum.

velocity, the Hugoniot state was obtained. The particle velocity was calculated from the measured free surface velocity by accounting for elastic-plastic interactions at the free surface [4]. The Hugoniot states are consistent with previous data [1] and the combined equation of state is: U_S = 4.78(0.02) + 1.42(0.02) u_p, where U_S and u_p are the shock and particle velocities, respectively (Fig. 2).

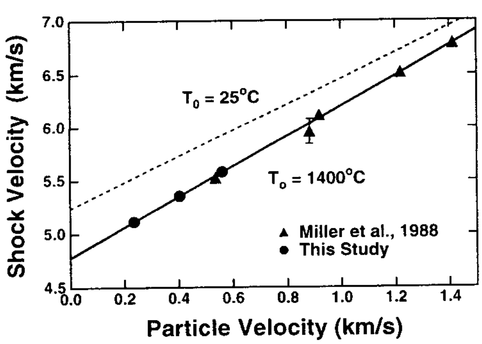

Fig. 2. Hugoniot equation of state of 1400°C molybdenum. Solid line is a least squares fit to the data. Dashed line shows the 25°C Hugoniot.

The elastic precursor manifests itself as a sharp jump in velocity which then relaxes by as much as 25%. No such relaxation was observed in Mo samples compressed from ambient temperature [5]. The amplitude of the Hugoniot elastic limit (HEL) is 1.46-1.73 GPa. HEL values for Mo compressed to 7-15 GPa from ambient temperature are 2.3-2.8 GPa for slightly thicker samples (6.1 mm) [5]. Thus, at 1400°C, the HEL amplitude of Mo is reduced by ~35%.

Assuming a von Mises yield condition, the compressive yield strength, *Y*, is related to the HEL amplitude through:

$$Y = \frac{(1-2\upsilon)}{(1-\upsilon)}\sigma_{\mathrm{HEL}}, \tag{1}$$

where υ is Poisson's ratio which is calculated to be 0.313 at 1400°C [3]. The yield strength at the HEL is 0.79-0.94GPa for the three experiments while the ambient T data of [5] yields Y = 1.3-1.6 GPa.

Material strength has been observed to decrease at high shock stress in aluminum, presumably because of thermal effects [6]. However, there is little quantitative information on thermal softening under dynamic compression. Yield strength is plotted as a function of initial temperature in Fig. 3. In the constitutive model of [7], thermal effects are approximated by assuming that the ratio Y/G is constant, where G is the shear modulus. According to Fig. 3, the yield strength of Mo decreases at a faster rate than the shear modulus. An alternative representation is that the yield strength is the following linear function of homologous temperature:

$$Y = 1.59(1-T/T_m), \tag{2}$$

where T_m is the melting temperature. This relationship was obtained from the 25°C yield strength at 12.6 GPa and by requiring that Y = 0 GPa at the melting point. This relationship predicts a yield strength at 1400°C of 0.65 GPa, 22-45% below the measured values.

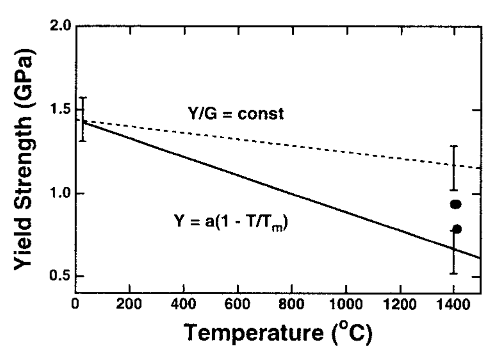

Fig. 3. Yield strength of Mo at the HEL as a function of initial temperature. Error bars show range of values from [5].

Unloading States

Decompression of the sample results from a rarefaction wave propagating from the rear of the impactor (Fig. 4 (inset)). Unloading wave velocities, V_P, calculated from the rarefaction arrival time and the known shock and release properties of the impactors are shown in Fig. 4. The 1400°C Hugoniot velocities are offset to significantly lower values than ambient temperature ultrasonic data to 0.5 GPa [5] extrapolated via finite strain theory. The decrease results from the effect of temperature on the elastic wave velocity.

Reflection of the shock from the Mo rear surface perturbs a region near the free surface through which the rarefaction wave must pass (Fig. 4, inset). The uncertainty thus introduced was minimized by including a correction term and by restricting the perturbed region to less than 10% of the sample thickness.

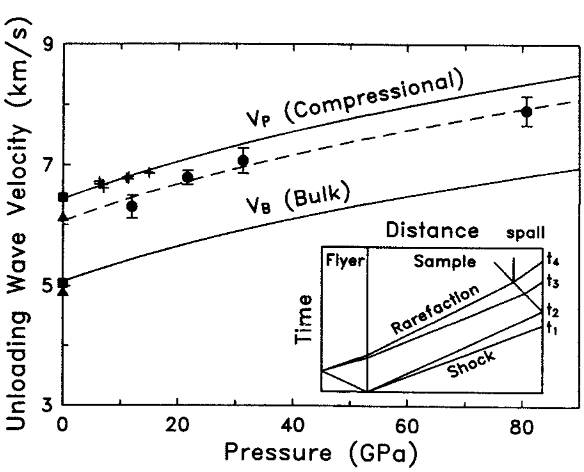

Fig. 4. Unloading wave velocity in molybdenum shock-compressed at 25°C (pluses) and at 1400°C (filled circles). The solid lines show extrapolated compressional and bulk velocities at 25°C. The dashed line is fit to the 1400°C Hugoniot velocities using Birch's Law. Inset is a distance-time diagram (in Lagrangian coordinates) of wave propagation through the flyer and sample.

The temperature coefficient of V_P was calculated from the Hugoniot and room temperature data at a given pressure:

$$\left(\partial V_P/\partial T\right)_P = \frac{V_P(H) - V_P(25^\circ\mathrm{C})}{T(H) - 25^\circ\mathrm{C}}, \tag{3}$$

where H refers to Hugoniot conditions. *T(H)* includes both the initial temperature and the shock-induced temperature increase which ranges from 129 ± 22°C at 12 GPa to 1037 ±186°C at 81 GPa.

At high pressure, Mo values are consistent with the ambient-pressure value of $\left(\partial V_P/\partial T\right)_P$ from ultrasonics [3] and suggest a decrease in $\left|\left(\partial V_P/\partial T\right)_P\right|$ with pressure. The highest pressure Mo data yield a 31-38% decrease in $\left|\left(\partial V_P/\partial T\right)_P\right|$ from -0.26 m/s/°C at ambient pressure to -0.16 m/s/°C (31 GPa) and -0.18 m/s/°C (81 GPa).

To examine the reliability of the extrapolated ultrasonic data, Hugoniot sound velocities were computed from wave profiles measured on Mo samples shocked from 25°C to 7-15 GPa [5], a region where shock heating effects are small. As shown in Fig. 4, the Hugoniot measurements are consistent with the ultrasonic data. Similar agreement between extrapolated ultrasonic data and Hugoniot measurements to 35 GPa has been observed for Al, Cu, and W [9] as well as for MgO [10]. It has been argued from micromechanical theory [11] that, due to plastic flow, the measured Hugoniot rarefaction velocity can be less than the elastic wave velocity. The results of Fig. 4 suggest this effect is not significant for Mo.

Acoustic velocities in Mo shock-compressed from a 25°C initial state to pressures between 150 and 441 GPa have also been reported [2]. These data indicate that a solid-solid phase transition occurs at around 210 GPa and Mo melts near 390 GPa. Fig. 5 compares available compressional and bulk sound velocity data for Mo, including ultrasonic [8], shock compression [this study, 2, 5], and isobaric expansion data [12]. The trend of the data between 150 and 190 GPa (ρ = 13.7-14.5 g/cm^3) differs significantly from the trend of the present data.

The interaction of unloading waves depicted in the inset to Fig. 4 leads to the development of tensile stresses within the specimen which leads to dynamic fracture. The characteristic signature of spall is the "pull-back" in free surface velocity seen in Fig. 1. From the amplitude of the pull-back signal, an estimate of the spall strength can be obtained [13]. Near 12 GPa, the spall strength of high-temperature Mo is found to be 2.4 GPa, only slightly different from the value of 2.31 GPa reported for room-temperature Mo

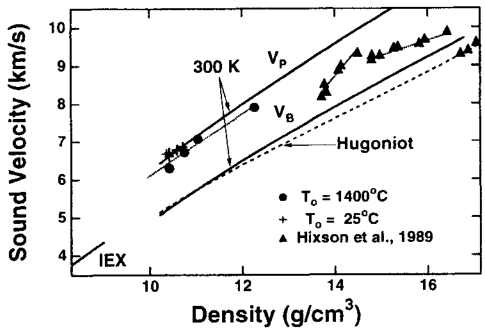

Fig. 5. Compressional and bulk sound velocity data for Mo. Solid lines are extrapolated ultrasonic data [8]. Dashed line is bulk velocity calculated from Hugoniot slope [2]. The solid circles are data from this study, while pluses and triangles are Hugoniot data from [5] and [2]. Dotted lines show linear fits to the data. IEX - isobaric expansion measurements on liquid Mo [12].

[14]. Thus, in contrast to the compressive yield strength, the spall strength appears to be temperature-insensitive for this material.

SUMMARY

Free surface velocities have been measured on molybdenum preheated to 1400°C in order to investigate its high-temperature properties under shock compression. Equation of state measurements on 1400°C Mo are in excellent agreement with the results of earlier streak camera experiments. The Hugoniot elastic limit stress ranges from 1.5-1.7 GPa between 12 and 31 GPa at ~1400°C, which is significantly below ~25°C values of 2.3-2.6 GPa. Spall-strength measurements near 12 GPa indicate this quantity is only weakly temperature sensitive in Mo.

Unloading wave velocities between 12-81 GPa lie 4-8% below extrapolated room temperature values. Velocity trends to 81 GPa are inconsistent with measured velocities between 150 and 190 GPa from a 25°C initial state [2]. This may be a consequence of high-pressure structural changes in Mo caused by electronic changes, but no evidence of anomalous effects are observed to 81 GPa in the high-temperature data.

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